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Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition

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[1] Global average trends in solar radiation reaching the Earth's surface show a transition from dimming to brightening that occurred in about 1990. We show that the inter-annual trend in solar radiation between 1980 and 2000 mirrors the trend in primary emissions of SO_2 and black carbon, which together contribute about one-third of global average aerosol optical depth. Combined global emissions of these two species peaked in 1988–1989. The two-decadal rate of decline in aerosol loading resulting from these emission changes, 0.13% yr^{-1}, can be compared with the reported increase in solar radiation of 0.10% yr^{-1} in 1983–2001. Regional patterns of aerosol and radiation changes are also qualitatively consistent. We conclude that changes in the aerosol burden due to changing patterns of anthropogenic emissions are likely contributing to the trends in surface solar radiation. **Citation:** Streets, D. G., Y. Wu, and M. Chin (2006), Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition, *Geophys. Res. Lett.*, *33*, L15806, doi:10.1029/2006GL026471.

1. Introduction

[2] Observations of the amount of solar radiation reaching the Earth's surface in the past few decades show unexpected trends that have thus far not been fully explained [*Wild et al.*, 2005; *Pinker et al.*, 2005]. There was a decline in the amount of sunlight reaching the Earth's surface ("dimming") from the beginning of measurements in 1960 until about 1990. Thereafter, the amount of sunlight reaching the Earth's surface appeared to increase ("brightening") until present time. This transition from dimming to brightening is extremely important for understanding ecosystem responses and other effects. Various explanations have been offered for the observed trend, including cloud-cover changes, aerosol changes, volcanic eruptions, and data artifacts. In this paper, we present for the first time annual trends in global and regional emissions of sulfur dioxide (as a precursor of sulfate aerosol) and black carbon from 1980–2000. We show that these primary emission trends mirror the insolation trends. Consequently, a likely cause of the observed transition from dimming to brightening is a change in the global aerosol burden arising from changes in primary anthropogenic emissions.

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2. Methodology

[3] In previous work [*Streets et al.*, 2003, 2004; *Bond et al.*, 2004] we reported the development of inventories of primary carbonaceous aerosol emissions, black carbon (BC) and organic carbon (OC). In that body of work we stressed the need to take a technology-specific view of aerosol emissions, due to the wide variation in emission rates for different types of combustion and control technologies. In particular, a detailed global inventory of primary BC and OC emissions was reported for the year 1996 [*Bond et al.*, 2004]. In order to examine trends in primary carbonaceous aerosol emissions, we have extended the 1996 inventory to an annual trend for the period 1980–2000. In addition, we have adapted the system to estimate SO_2 emissions over the same period.

[4] To calculate emissions we use annual fuel-use trends by world region and economic sector contained in the IMAGE model [*National Institute for Public Health and the Environment (RIVM)*, 2001], developed for the Intergovernmental Panel on Climate Change (IPCC), processed into 112 technology/fuel combinations [*Streets et al.*, 2004]. The only modification made to the energy data over the period 1980–2000 was a replacement of the IMAGE data for China by a more accurate representation of historical coal use obtained from official Chinese energy statistics [*Streets and Aunan*, 2005]. Annual emissions were estimated for 17 world regions with incorporation of the major time-dependent trends in emission control technology, emission control regulations, and coal sulfur content.

3. Emission Trends

[5] Figure 1 shows the annual trends in SO_2 emissions for six industrialized world regions (upper) and six developing regions (lower). These trends are in good agreement with other global and regional SO_2 estimates [*Grübler*, 1998; *Smith et al.*, 2001; *van Aardenne et al.*, 2001]. They show, for example: (a) the break-up of the Soviet Union in 1987–1991 and the resulting decline in industrial production and atmospheric emissions; (b) the decline in emissions in OECD Europe throughout the period due to environmental regulations; (c) the effect of the 1990 Clean Air Act Amendments in the U.S. to initiate a decline in emissions after 1992; and (d) a sharp increase in emissions in East Asia (China) until the late-1990s that was halted by the combined effects of the Asian economic crisis, energy efficiency improvements, and restructuring of state-owned industries [*Streets et al.*, 2001]. Increasing emissions in the developing countries, led by India and Southeast Asia, reflect rapid economic and social development driven by growing fossil-fuel use and relatively lax emission controls.

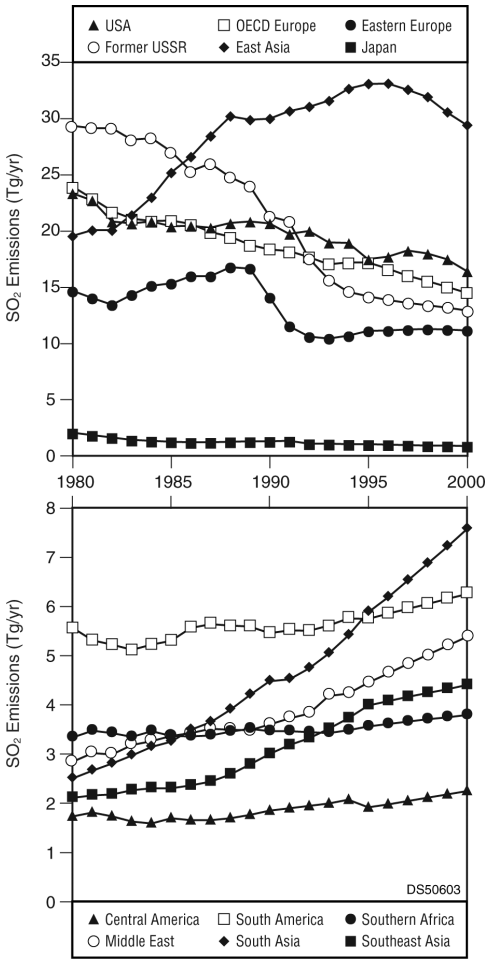

Figure 1. Trends in SO_2 emissions, 1980–2000, by world region: industrialized regions (upper), developing regions (lower).

[6] Figure 2 shows similar trends in BC emissions for the same world regions. Though both SO_2 and BC are the products of fuel combustion, the trends are not the same for two main reasons: (a) BC is produced mostly from incomplete combustion in small, low-temperature facilities and not power plants or large industrial facilities, whereas SO_2 emissions are closely related to total coal and oil use; and (b) a significant amount of BC is produced from biofuel combustion and open biomass burning, whereas vegetative fuels generate little SO_2. Thus in Figure 2 East Asia shows significantly higher BC emissions than other regions because of extensive coal and biofuel use in the household sector [*Streets and Aunan*, 2005]. The decline of BC emissions in East Asia began earlier than SO_2 emissions, 1988 versus 1995, when coal use in the household sector became increasingly undesirable in urban areas. In most other industrialized regions, BC emissions declined as a result of environmental pressures to reduce vehicle particulate emissions and to eliminate "smoky" facilities of all kinds. Such pressures have been less successful in the developing world.

[7] We have also estimated the trends in primary OC emissions over the same period (not shown). OC emissions are roughly constant at 33.7 (±0.3) Tg yr^{-1}, due to the dominance of open biomass burning. In our work, which is a modification of the way biomass burning is treated by the IPCC [*Streets et al.*, 2003, 2004], we only include those trends in biomass burning that are due to fluctuating land-use patterns and related human activities. Such changes are small over this 20-year period. For our purposes, we can consider that open biomass burning emissions add only noise to the trend, presuming that no systematic modification of burning patterns occurred during 1980–2000. We are not able to estimate the trends in secondary organic aerosol formation at this time.

[8] Globally, SO_2 emissions declined briefly from 69.0 TgS in 1980 to 65.9 TgS in 1982, though prior to the 1980s SO_2 emissions had been generally increasing, as shown by longer-term emission trends [*van Aardenne et al.*, 2001]. Deng Xiaoping's constitutional reforms in 1982 marked the beginning of a period of rapid growth in the Chinese economy that led to a spurt in SO_2 emissions (Figure 1). After 1982 we estimate that global SO_2 emissions systematically increased to a peak of 70.7 TgS in 1988 and 70.2 TgS in 1989. Thereafter, SO_2 emissions declined to 61.5 TgS in 2000. The overall rate of decline between 1980 and 2000 was 0.57% yr^{-1}. Global BC emissions show a similar but not identical trend, rising from 8.24 TgC in 1980 to a peak of 8.38 TgC in 1988 and then falling to

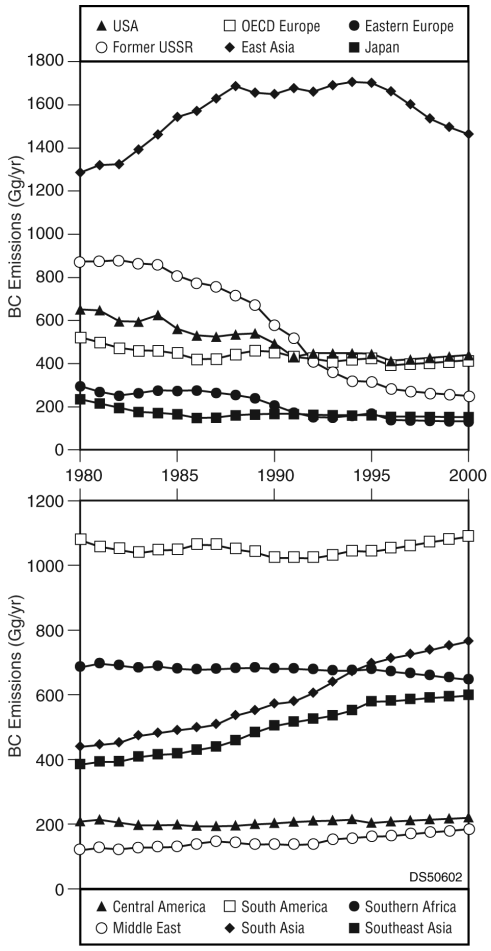

Figure 2. Trends in BC emissions, 1980–2000, by world region: industrialized regions (upper), developing regions (lower).

Table 1. Emissions, Mass Burdens and Aerosol Optical Depths for the Major Global Aerosol Types

Aerosol Type	Source Strength,[a] Tg yr^{-1}			Atmospheric Burden,[b] Tg yr^{-1}	Aerosol Optical Depth (at 550 nm)[b]	Aerosol Optical Depth, %
	Manmade (This Work)	Other	Total			
Sulfate[c]	61.5–70.7	19.4	80.9–90.1	0.58–0.65	0.0290–0.0323	28–30
BC[c]	7.96–8.38	0	7.96–8.38	0.12–0.13	0.0025–0.0027	2.4–2.5
OC			72.9	1.04	0.0143	13–14
Dust			3154	29.25	0.0342	31–33
Sea salt			9738	13.27	0.0254	23–24
All					0.105–0.109	100

[a]Source strengths for OC, dust and sea salt are taken from the GOCART model for the year 2000 [*Chin et al.*, 2002]. Sulfate source strength is quantified as primary emissions of SO_2 in TgS.

[b]Global average atmospheric burden and aerosol optical depth are converted from the source strength based on GOCART model simulations [*Chin et al.*, 2002, 2004].

[c]Ranges shown in the data for sulfate and BC represent the range of values in the 20-year trend, min–max.

8.01 TgC in 2000. Thus, both SO_2 and BC emissions show peaks in 1988–89 for the two-decadal period. The overall rate of decline in BC emissions between 1980 and 2000 was less than for SO_2, just 0.14% yr^{-1}. Uncertainty in our global SO_2 emission estimates, measured as 95% confidence intervals according to previously documented methodology [*Streets et al.*, 2003], is ±14% (consisting of ±9% for developed countries; ±13% for industrializing countries like China, FSU, and Eastern Europe; and ±38% for developing Africa, Latin America, etc.).

4. Consequent Trends in Aerosol Optical Depth

[9] For the purposes of comparing the effects of these SO_2 and BC emission changes on the global aerosol burden and consequent changes in average global aerosol optical depth (which can then be compared with the solar radiation trend), we have incorporated the other major aerosol types in Table 1. Here we use results from GOCART c3.1 model simulations [*Chin et al.*, 2002, 2004]. We include the contributions from volcanic SO_2 (6.8 TgS yr^{-1}), dimethyl sulfide (12.6 TgS yr^{-1}), primary and secondary OC combined (72.9 TgC yr^{-1}), mineral dust (3,154 Tg yr^{-1}), and sea salt (9,738 Tg yr^{-1}). We assume there are no systematic trends in any of these source strengths over the 20-year period.

[10] These source strengths are then converted to global aerosol burdens and global average aerosol optical depths at 550 nm, as described previously [*Chin et al.*, 2002, 2004]. We estimate that the global average aerosol optical depth decreased from 0.108 in 1980 to 0.105 in 2000. Because dust and sea salt are less efficient in extinction of radiation, the contribution of sulfate + BC represents as much as one-third of the total extinction, and their joint contribution declined from 32.5% in 1980 to 30.4% in 2000. Figure 3 shows the contributions of all aerosol species to global average aerosol optical depth, which increased by an average of 0.08% yr^{-1} between 1980 and 1988 and declined by an average of 0.27% yr^{-1} between 1988 and 2000. For the entire two-decadal period, global aerosol optical depth declined by 0.13% yr^{-1}. Since the aerosol direct radiative effects at the surface are linearly proportional to the aerosol optical depth (i.e., the higher the optical depth, the less solar radiation reaches the surface [*Sheridan and Ogren*, 1999]), we argue that the same trend should apply to the change in surface radiation budget, all other things being equal (see section 5).

5. Discussion and Conclusions

[11] The calculated trends in emissions and aerosol optical depth are consistent with the measured global trends in solar radiation observed at the Earth's surface. An overall increase in surface solar radiation between 1983 and 2001 of 0.16 W m^{-2} yr^{-1}, or 0.10% yr^{-1}, was reported [*Pinker et al.*, 2005]. These authors also report that the satellite-based record of surface solar fluxes suggests some dimming until 1992, followed by an increase. *Wild et al.* [2005] report a decrease of sunlight from 1960 until the late 1980s and a widespread brightening thereafter. The increase from 1992 to 2002 for a variety of global sites is 0.68 W m^{-2} yr^{-1}.

[12] By inspection, our regional emission trends (Figures 1 and 2) are also qualitatively consistent with solar radiation trends observed at specific measurement sites—which they should be due to local influences on radiation arising from enhancements of aerosol concentrations in the vicinity of high emission areas. In fact, urbanization has been sug-

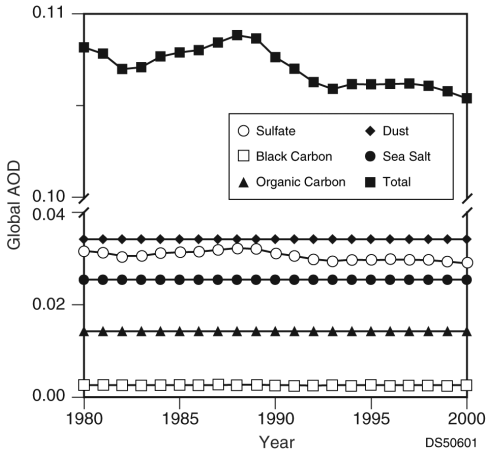

Figure 3. Trends in global average aerosol optical depth, 1980–2000. OC, dust, and sea salt are included as constant values over this time period, solely for illustration of their relative contributions to the total; we recognize that they have a natural variability that has thus far not been quantified.

gested as the cause of global dimming [*Alpert et al.*, 2005], which is consistent with our interpretation. Among the regional trends reported are: (a) a change from dimming to brightening over Europe in about 1985 [*Wild et al.*, 2005]; (b) a decrease in solar radiation in the Swiss Alps from 1981 to 1995, followed by an increase between 1995 and 2003 [*Pinker et al.*, 2005; *Philipona and Dürr*, 2004]; (b) a similar transition from dimming to brightening in the Former Soviet Union in the 1980s [*Wild et al.*, 2005]; (c) the decline of solar radiation in China leveling off in the 1990s [*Wild et al.*, 2005; *Liu et al.*, 2004]; (d) a continued increase in dimming into the 1990s over India [*Wild et al.*, 2005]; (e) an ongoing decline in surface solar radiation in Zimbabwe [*Wild et al.*, 2005]; (f) only a small increase in extinction during the period 1978–1997 in Chile [*Schwartz*, 2005]; and (g) a decline in surface solar radiation in the United States during the period 1961 to 1990 [*Liepert*, 2002]. An important next step in confirming our hypothesis will be a quantitative comparison of regional emission trends with solar radiation trends at long-term surface observation sites.

[13] While the similarities between the aerosol trends and the solar radiation trends are compelling, we acknowledge that there are a number of other factors to be considered. In their commentary on the two radiation trend papers, *Charlson et al.* [2005] urged caution in attempting to quantify and explain changes in the Earth's radiation balance. Long-term changes in cloud cover are poorly understood, but to the extent that any such systematic trends have occurred in recent times, they may be linked to aerosol interactions. The large volcanic eruptions of El Chichon (1982) and Pinatubo (1991) undoubtedly added considerable fine particulate matter to the atmosphere, which influenced at least regional if not global extinction for a year or two [*Schwartz*, 2005]. Finally, the different techniques used to measure surface radiation have yet to be fully intercompared. It will take a combination of consistent measurements and detailed emission trends tested within global models to fully confirm or refute the explanation of the dimming/brightening transition offered in this paper.

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